Streamflow Regulation Accounting
South Platte Implementation Plan

Background

As part of its plan to provide Advanced Hydrologic Prediction Service (AHPS), the National Weather Service (NWS) is using the NWS River Forecast System (NWSRFS) to prepare long-range probabilistic forecasts of streamflow. The Missouri Basin River Forecast Center (MBRFC) is preparing to implement AHPS in the South Platte river basin. The presence of extensive systems of streamflow regulation to capture and regulate or divert runoff throughout the South Platte basin will require careful analysis and the design of unique solutions to model the effect of this regulation in developing forecasts.

This document outlines a plan for the implementation of models and strategies to account for streamflow regulation in the South Platte. It is being prepared under task no. 3-0001 of AHPS Contract DG133W-03-CQ-0021. This document draws from and expands upon previous documents prepared under the same task. These include a document titled "*Streamflow Regulation Issues and Solutions Identification"* (*Issues Identification*) which was distributed to each RFC with a request for feedback; a memo dated 22 March, 2004 titled "*Streamflow Regulation Issues* Summary" which summarized feedback from the RFCs; a memo dated 26 March, 2004 titled "*General Streamflow Regulation Modeling Strategies*" (*General Strategies)*; and a memo dated 26 March, 2004 titled "*South Platte Streamflow Regulation Modeling Strategies*" (*South Platte Strategies*).

The implementation plan presented below is adapted from the *General Strategies* memo and outlines a recommended approach to implementation of streamflow regulation accounting for the South Platte. The main activities of the plan are a basin inventory, data analysis and synthesis, development and testing alternatives, and NWSRFS implementation. One objective of the plan development is to assess the level of effort necessary to successfully implement regulation accounting in the South Platte. The effort required will depend both on the complexity of the regulation that is discovered during the basin inventory and data analysis phases as well as on the level of detail that is eventually selected for the solutions that are to be implemented. In order to provide a baseline estimate of the required level of effort and to help the RFC better appreciate the specific modeling challenges and requirements in the South Platte, RTi is undertaking much of the basin inventory activity as part of the current task. Initial results of this effort to date are included as an appendix titled "*South Platte Basin Characterization.*" The information in the appendix will help guide future discussions and decisions regarding modeling approach and associated level of effort.

A preliminary estimate of the required level of effort for implementation is presented following the implementation plan. This estimate is based on RTi's understanding to date of the regulation in the basin and broad assumptions regarding appropriate levels of detail in the modeling. As noted previously, the effort required will ultimately depend on the complexity of the regulation and the detail and complexity of the solutions that are identified and implemented.

Implementation Plan

The South Platte forecast group does or will include about 45 segments, most of which include significant regulation effects. The Snow and Sacramento model parameters for nearly all of the segments in the South Platte conform to a set of regional parameters derived from one or two sub-basin calibrations within the basin. MBRFC recognizes the need to update these hydrologic model parameters throughout the South Platte as part of its AHPS implementation. An approach to hydrologic model calibration is included in this implementation plan because of the overlap between the data processing that will be required for streamflow regulation modeling and for hydrologic model calibration. The major activities in the implementation plan are a basin inventory, data analysis and synthesis, design and testing of alternatives, and implementation in NWSRFS.

Basin Inventory

Objective

The objective of the basin inventory is to collect as much information as possible in order to adequately understand the regulation in the South Platte. The primary questions that need to be answered at this stage are 1) What types of regulations are affecting the river, 2) Where are these regulations occurring, 3) Who is responsible for the regulations, and 4) Why do they operate as they do. This information provides the basis for making qualitative assessments of the relative streamflow impacts caused by the various regulation issues.

Steps

Basin Overview: An initial review of the basin is required to establish for the various parties involved in the study the basin characteristics, major water uses, and other important facts. This overview will provide context and direction for further investigation.

Regulation Identification: The next level of investigation requires identification of both regulation types and regulating entities within the South Platte. In considering regulation types it is important to distinguish between physical structures and the policies and uses that govern the operation of those structures. Both must be identified and characterized. Regulating entities in the South Platte are so numerous as to prohibit identification of all of them, but the major regulators can be identified, as well as important groupings and cooperatives composed of individual regulators. Given the NWS role in preparing and disseminating forecasts, there should be some channels of contact already established that could be used to gain access to available information. It will be necessary to initiate new contacts as well as to learn more about regulation objectives and obtain needed information.

Information Collection: Several different types of information are required to fully describe streamflow regulation, including the following:

- Data - Time series observations including streamflow, diversions, reservoir levels and releases, and other hydrologic features are necessary for subsequent data analysis and processing. These data are available from a variety of sources including the USGS, the State of Colorado, and records from major public regulators.

- Basin Administration: Administrative records for the 13 water districts in the South Platte provide an overview of the past water years and typically highlight any type of exceptional operational action. These detailed records could be obtained to shed light on specific issues that may arise in a specific basin. The effort required to obtain and evaluate these records in a comprehensive way is probably not justified.

- Operational Information: Published operating plans and reports, including annual operating reports provide the basis for defining model parameters and developing operational rule curves. Many private regulating entities do not publish reports making data acquisition more difficult.

Reports and plans can be obtained from USBR and USACE. Additional effort and specific knowledge of available reports and plans will be required to request and obtain information from Denver Water and other regulators.

- Existing Studies and Reports: Hydrologic/Engineering studies are an important resource and can provide a significant amount of insight into the river system. As with operating plans and reports, specific knowledge of available studies will be necessary to know what to ask for. Personal visits to the regulator's site may be required.

- GIS / Maps: USGS quad maps and GIS data provide the means to identify spatial distribution and location of regulating structures. Much of this information is available to RTi as a result of previous and ongoing studies of the South Platte. Other information is already available at the RFC.

High Level Basin / Segment Characterization: At an early stage individual segments need to be evaluated and characterized to identify strategic issues. This activity can help to guide parallel software development activities and can help to estimate level of effort in implementation and set expectations for the level of accuracy that may be achieved in the regulation modeling effort. Segments should be characterized in terms of general hydrology, operations, and administration. Key regulation points and practices that have the capacity to affect multiple segments also must be identified.

Data Analysis and Synthesis

Objective

The objective of this activity is to isolate and analyze regulations in each individual segment and then synthesize this information at a system level. It is important to determine both how the regulation impacts the streamflow as well has how variation in the streamflow impacts regulation practices. It also is necessary to identify those regulations that transcend the boundary of a single segment and evaluate their range of influence, both upstream and downstream. Ultimately, the way in which all of the different regulators/regulations interact and affect one another and how they manage to operate together in a single, integrated system is determined.

Steps

Develop Control Volume Diagrams: These diagrams help to identify and describe all inputs and outputs to and from a segment. Typical elements in a diagram would include inflow from an upstream segment, diversion and return flow for irrigation or other uses internal to the segment, diversion to off-channel storage, diversion for irrigation or other use outside of the segment, imports from other segments, reservoir regulation within the segment, and groundwater pumping with any associated return flows. Arrows are drawn to indicate inflows and outflows from the segment and are labeled according to the type of element represented. Finally, the various elements of the diagram are annotated with more detailed information where available and appropriate. For instance, mean monthly diversions may be tabulated, or a note indicating the ultimate destination of a diversion or the owner of a reservoir may be added.

Time Series Development: Time series are developed for many of the segments to aid in subsequent analysis and calibration. The most basic set of time series that need to be compiled for a non-headwater segment are mean areal precipitation, mean areal temperature, sub-basin inflow, and sub-basin outflow. These time series are necessary for hydrologic model calibration. Additional time series that are compiled where possible include diversions, return flows, pumping, basin imports, and reservoir inflows, outflows, pool elevations, and withdrawals. In the South Platte, a significant amount of effort will be devoted to converting data from many different formats into aggregated time series data that can be used in the analysis and later modeling steps.

Water Balance: Based on available time series for each segment a water balance analysis is conducted to estimate the sub-basin runoff coefficient and compare it with surrounding basins and to detect inconsistencies that may suggest missing regulation elements that alter the flow or potential errors in the underlying data.

Develop Naturalized Flows: Naturalized local flows can be calculated by adding and subtracting upstream inflows and regulating effects at the downstream gage. These results are used to calibrate hydrologic models and would be developed specifically for areas where hydrologic models will be calibrated. Naturalized flows would be required at all segments if a complete historical simulation of the entire system is to be compared with historical observations during the calibration step, but this is not likely to be attempted due to the difficulty of collecting all of the necessary data at a daily time step and the fact that the system being developed will only represent historical conditions for the most recent years.

Classify/Aggregate Regulations: Regulation can be classified by magnitude, frequency of occurrence, seasonality, and other relevant factors that result in specific patterns. Regulations that have similar operations and effects upon streamflow are considered for aggregation in representing the regulation effect.

Identify System Dynamics: With the understanding established by the foregoing analysis, it should be possible to outline comprehensive overview of regulation effects in the basin, including both local (within segment) and system (spanning several segments) regulation. This will be helpful in defining groups of segments within the system where regulation dependencies are confined (i.e., boundaries beyond which upstream regulation is not dictated by downstream conditions).

Design and Test Alternatives

Objective

The objective of this activity is to associate streamflow regulation issues with viable modeling strategies using NWSRFS operations to represent regulation in the basin. Regulating operations, and the rules that govern them, are conceptualized in such a manner as to be translated into the NWSRFS modeling environment. This process must be performed on a segment-by-segment basis for localized regulations, as well as on a wider scale for regulations with downstream and other dependencies.

Steps

Identify alternatives: Various alternatives are considered to represent streamflow regulation issues in the basin. This is generally done on an individual segment basis as well as on a system-wide basis. In this phase the focus is on possible solutions to individual regulation issues, whether local or system-wide. Strengths, weaknesses and tradeoffs are identified.

Outline modeling plan: Having identified and evaluated alternatives, a comprehensive modeling plan is developed consistent with an overall level of detail, effort, and complexity that have been chosen for the implementation. The specific models and segment groupings are identified and conscious choices are made about which regulation activities and effects will and will not be represented by the selected modeling plan. The term "segment" is used loosely here to refer to simulation/forecast points, since new segments may be introduced to handle local flow calculation, time series manipulation operations, and reservoir system simulations.

The sub-basins where hydrologic models will be calibrated are also finalized, recognizing that the necessary time series must have previously been prepared. Several factors are considered in selecting sub-basins to calibrate. Most of the headwaters are considered for calibration, particularly if they are free of internal regulation effects. Several non-headwater areas will probably need to be calibrated to be representative of changing hydrologic factors in various parts of the basin. Areas with little internal regulation and high quality discharge time series at upstream and downstream ends are the most promising areas.

Test modeling approaches: The modeling plan will include combinations of operations that have not been combined before in the manner chosen. The more innovative modeling approaches will need to be evaluated in a test implementation to check for conceptual flaws and overall ability to represent the regulation issues.

NWSRFS Implementation

Objective

The objective of the NWSRFS implementation is to develop and refine calibration decks that represent the system defined in the modeling plan, assure their suitability in the forecast system, and to implement the changes in the operational forecast system.

Steps

- *Calibrate hydrologic models*: The Snow and Sacramento models are calibrated according to standard procedures using the time series prepared previously. Regional parameters sets are defined to be applied to adjoining basins with similar characteristics but which were not explicitly calibrated. Unit hydrograph and routing model parameters are reviewed as part of the hydrologic model calibration process. For purposes of estimating the level of effort that will be required it is assumed that 12 headwaters and 4 local areas will be calibrated.

- *Calibrate streamflow regulation models:* Calibration decks for each segment and segment grouping are assembled, tested, and calibrated. While hydrologic model calibration generally involves repeated parameter adjustment, calibration of regulation models will require repeated re-arranging of operations and combinations of operations, together with parameter adjustments, to fine-tune the modeling plan and improve the simulation results.

  The CONS-USE model will require calculation of irrigated area and specification of crop coefficients, irrigation efficiency, return flow accumulation rate, and a return flow recession rate among others. Special approaches will be required to couple the model with reservoir models to simulate demand that is met through reservoir releases when instream flows are insufficient. It is estimated that more than 20 different CONS_USE models will be calibrated.

  The TATUM routing model may be implemented in a variety of locations to process flow from various flow levels (or layers) to represent diversions. Other operations including WEIGH-TS, ADD-SUB, MULT-DIV, LOOKUP, and LOOKUP3 may be used to manipulate time series to reflect regulation practices.

The RES-J model will be implemented for individual physical reservoirs where specific reservoir characteristics and operating plans are available, for systems of reservoirs and diversions where upstream regulation is dependent on downstream conditions, and for composite reservoirs representing multiple reservoirs within a segment that share common operating characteristics. The individual reservoirs represented by a composite reservoir model are not large enough individually to justify a separate model, but collectively exhibit a pronounced effect on the sub-basin runoff characteristics. Each RES-J model requires separate parameterization of each reservoir, design of methods and method interactions through rules, and calibration of method parameters to reproduce observed regulation effects. It is estimated that 25 or more separate reservoirs will be simulated in various combinations of RES-J models.

- *Evaluate the success of the models:* Consider the degree of improvement in capturing regulation effects compared to the previous modeling approach. Test the implementation in an ensemble forecast mode to verify proper functioning and to evaluate results, including the use of "hindcasting."

- *Re-define system*: Re-define the segments and re-structure the forecast system configuration as needed. Note that ensemble forecasting mentioned in the previous step can only be performed after the system re-definition is complete. Required effort for these activities has been estimated, they should be considered in light of the likelihood that the RFC will perform them.

Management

Effective execution of the implementation plan requires attention to schedule and resource constraints and monitoring to assure that the appropriate level of effort is being allocated to the various activities as they progress. Effective communication of progress and intermediate results will require periodic progress reports, documentation of intermediate results, and review meetings to present results and set direction for ongoing activities.

Level of effort

The following table presents an estimate of the level of effort that will be required to implement streamflow regulation models according to the plan outlined above. The level of effort is represented by the estimated number hours required to complete each activity. These hours represent total hours with a typical distribution among management, senior engineering and engineering staff. Inasmuch as some of this work has been completed, an estimate of the current percent complete for each activity is also given.

Activity	Estimated Hours	Percent Complete
Basin Inventory	476	65%
Data Analysis/Synthesis	1,014	-
Develop Alternatives	360	-
NWSRFS Implementation	4,404	-
Task Management	328	-
Total	6,582	-

Neither the full scope of implementation activity nor the required level of effort presented above have been defined with a great deal of certainty. A useful result could certainly be obtained with a more modest level of effort, just as improved accuracy could be obtained with an increased level of effort. At the current level of investigation it is difficult to know or express the degree to which a given level of effort will produce models that accurately reflect streamflow regulation effects on the South Platte. It is hoped that some progress in this regard will be made through future discussions of the material presented here and in the appendix. One approach that could be tried would be to proceed on a subset of the basin with a modest level of effort to model the regulation, followed by an evaluation of the quality of the simulation of historical regulation. Decisions could then be made regarding extension of the modeling approach and associated level of effort to the remainder of the basin.

NWSRFS Enhancements

In the *General* Strategies memo RTi outlined a number of potential enhancements to current NWSRFS operations. Following is a discussion of needs and enhancements that might be considered to facilitate regulation modeling specifically on the South Platte. Many of the enhancements noted in the *General Strategies* memo are repeated. Ideas for additional enhancements will undoubtedly arise as this implementation effort proceeds. The effort required to implement these enhancements is not currently included in the estimated level of effort outlined above. Planning for the South Platte implementation needs to be consistent with the priorities that are established for NWSRFS enhancements, and scheduling of the implementation needs to be coordinated with the schedule for NWSRFS enhancements so that the appropriate tools will be available as planned when they are needed for modeling and initialization.

- Diversions from a point on the river are often made to meet downstream consumptive use demands or water rights. The actual releases may be a function of a number of variables including the demand, the magnitude of the water right, available storage in the system, and current streamflow at the diversion or at another point in the system. There is little flexibility in NWSRFS to model diversions based on these variables.

- Irrigation diversions and subsequent consumptive use depend both on the demand and the availability of streamflow or reservoir storage. The current consumptive use model is limited in that does not consider the availability of reservoir storage when estimating diversions.

- Irrigation diversions are often made to meet demand in a different segment than the one from which the diversion was made. Return flows then usually apply to the segment where the irrigation takes place. The CONS-USE model currently does not provide flexibility to distinguish between the point of diversion and the point of return flows.

- Consumptive use demand may be met in whole or in part by precipitation over an irrigated area. This often results in a temporary reduction in diversions. This effect is not modeled currently by the CONS-USE operation and represents a limitation in its capability.

- Losses, gains, and diversions from a channel are a complex function of many variables. One approach to representing these losses is through the CHANLOSS operation. This operation is currently limited to fixed monthly loss rates and loss as a linear function of discharge.

- Conveyance losses in a canal or channel are often not lost from the system altogether, but appear later as return flows. It would be useful to be able to track and transform these losses according to some storage and return flow function.

- In modeling streamflow regulation, it is often necessary to manipulate time series in a variety of ways. Operations that are currently used to accomplish this include CLEAR-TS SET-TS, WEIGH-TS, ADD-SUB, LOOKUP, LOOKUP3, and MULT-DIV. None of these operations currently allow relationships to be defined as a function of the date, and the need to employ multiple operations to perform fairly simple arithmetic procedures can result in complicated operations tables.

Potential solutions to these issues could be drawn from a combination of new operations and enhancements to existing operations in NWSRFS, as described in the following list. Each enhancement includes an initial assessment of the priority of the enhancements, assuming that the implementation will begin with the Poudre River in the north part of the South Platte and conclude with the headwaters of the South Platte above the City of Denver.

CONS_USE

- Currently, the operation requires specification of an input streamflow time series from which the diversion will be withdrawn. Specification of the input time series could be optional to make it easier to simulate a case where the water source is a reservoir. *Priority: High*

- Currently, return flows are assumed to return to the diversion point and are available for diversion. In many cases return flows return well downstream of the diversion point, or even exit the basin. Allowing the user to specify if the return flows are available for diversion would provide the user more flexibility in the use of the operation. *Priority: High*

- An option could be included to have the operation compute return flows only, and to do so based on a given diversion time series. This would reflect situations where the actual diversion and subsequent return flow were limited by factors other than those currently considered in the operation. *Priority: High*

- An MAP input time series could be introduced to the operation and an accounting for the demand satisfied by precipitation could be added. *Priority: Moderate*

LOOKUP3

- The LOOKUP3 operation could be enhanced to allow a date to be specified as one of the independent variables. *Priority: High*

CHANLOSS

- The operation could be expanded to include an option to allow the computed loss or gain be a non-linear function of discharge. *Priority: Low*

- This operation computes the resulting streamflow after the loss or gain is accounted for. It might be useful to generate a time series representing the actual gain or loss in addition to the resulting streamflow. *Priority: Low*

RES-J

- A new method could be added to RES-J to compute release as a function of additional system variables, states, or time series value, similar to the capability found in LOOKUP3. *Priority: High*

- A new method could be created that would make it easier to compute a reservoir release based on a consumptive use demand in a downstream part of the basin. *Priority: Low*

- The rules capability could be enhanced to allow testing on additional variables, e.g., time series values and linear combinations of states. *Priority: Low*

- One or more methods could be developed to allow diversion from a node as a function of current flow at the node, consumptive use demand, or other model states. *Priority: High*

Equation tool

- A new operation could be added that would permit arithmetic operations to be performed on time series. It could follow the form $t = \mathrm{A}x + \mathrm{B}y + \mathrm{C}z + \mathrm{D}x2 + \mathrm{E}y^2 + \mathrm{F}z^2 \ldots$ where t is the output time series, x, y, and z are input time series, and A – F are constants. Additional terms could be added to include logarithms and inverses of time series values. *Priority: Moderate*